

The extent of NGC 6822 revealed by its C stars population

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ABSTRACT

Using the CFH12K camera, we apply the four band photometric technique to identify 904 carbon stars in an area $28' \times 42'$ centered on NGC 6822. A few C stars, outside of this area were also discovered with the Las Campanas Swope Telescope. The NGC 6822 C star population has $\langle I \rangle = 19.26$ leading to a $\langle M_I \rangle = -4.70$, a value essentially identical to the mean magnitude obtained for the C stars in IC 1613. Contrary to stars highlighting the optical image of NGC 6822, C stars are seen at large radial distances and trace a huge slightly elliptical halo which do not coincide with the huge HI cloud surrounding NGC6822. The previously unknown stellar component of NGC 6822 has a exponential scale length of $3.0' \pm 0.1'$ and can be traced to five scale lengths.

Subject headings: galaxies: individual (NGC 6822) — galaxies: stellar content; structure — stars: carbon

1. INTRODUCTION

NGC 6822 is a barred dwarf galaxy of type IrIV-V (van den Bergh 1968), a classification similar to the Small Magellanic Cloud. Hubble (1925) discovered Cepheids in NGC 6822 and could conclude that it is a relatively nearby galaxy. NGC 6822 has recently been the subject of detailed multi-color investigation by Gallart, Aparicio & Vílchez (1996). We adopt, for NGC 6822, their determined color excess $E(B-V) = 0.24 \pm 0.03$ and true modulus $(m - M)_o = 23.49 \pm 0.08$. The abundance of two supergiants of NGC 6822 has recently been determined, from high resolution spectroscopy, by Venn et al. (2001). We adopt their estimate, $[Fe/H] = -0.49$, for the metallicity of NGC 6822.

NGC 6822 is nearly unique among the Local Group galaxies by having a huge hydrogen

envelope, several times bigger than its optical core (Robert 1972, Gottesman & Weliachew 1977, de Blok & Walter 2000). IC 1613 (Lake & Skillman 1989), the highly reddened galaxy IC 10 (Huchtmeier 1979) and to a lesser extent, NGC 3109 (Barnes & de Blok 2001) have also a similar HI envelope. The global structure of NGC 6822 was first surveyed by Hodge (1977) and in more detail by Hodge et al. (1991) who could trace the galaxy to 10' from its center. Hodge adopted the point of view that the outer structure of NGC 6822 is circular rather than following the shape of the bar. Because NGC 6822 is at a rather low Galactic latitude, $b = -18.4^\circ$, the low density periphery of the galaxy is masked by the foreground stars. The exact size of NGC 6822 is rather difficult to establish simply from star counts. The NASA/IPAC Extragalactic Database (NED) quotes a dimension of $15.5' \times 13.5'$ which is much smaller than the HI envelope mentioned above but is quite in line with Hodge's study.

All photometric surveys of NGC 6822, with the exception of the one by Hutchings, Cavanagh & Bianchi (1999) have targeted the obvious central part of the galaxy. Hutchings et al. (1999) have obtained HST photometry in two small regions located ~ 2 kpc from the optical center of NGC 6822. They detected the presence of main sequence stars extending to $2 M_\odot$ in the western field and suggest that this population might be the result of a tidal event. The presence of an hydrogen tidal arm was suggested by the HI map of de Blok & Walter (2000).

Cook, Aaronson & Norris (1986), who pioneered the photometric technique we are now using, were the first to target NGC 6822 in search of C stars. They observed two small ($1.5' \times 2.5'$) fields located along the central bar on opposite sides, a few arcminutes from its geometrical center. Some fifty C stars were identified, spectra confirmed the nature of the C stars (Aaronson et al. 1984) and led to the discovery of the first S star in NGC 6822 (Aaronson, Mould & Cook 1985). That investigation observed barely 3% of the area of

NGC 6822, if we assume the dimensions given by NED.

Battinelli & Demers (2000) have obtained a preliminary relation linking the number of C stars in a galaxy with its integrated absolute visual magnitude. This relation predicts that galaxies with $M_V < -15$ would have more than a few hundred C stars, NGC 6822 with $M_V = -15.2$ (Mateo 1998) should have at least 500 C stars. Such large number would provide sufficient statistics to investigate the extent of NGC 6822. A survey of the periphery is particularly interesting for a galaxy such as NGC 6822. Indeed, tidal interaction as been proposed (de Blok & Walter 2000) to explain the asymmetric shape of the extended hydrogen disc. It is reasonable to expect that the spatial distribution (and kinematics) of stars as old as ~ 3 Gyr could also have been influence by the presumed tidal interaction. On the other hand, the huge HI envelope, currently visible, implies that, if a gravitational interaction took place, it must not have been strong enough to drastically disturb the gas. In this respect, C stars have a distinctive advantage, over deep multi color surveys, the foreground contribution is zero!

On a more global scale, in order to compare the C star population of different galaxies one must be careful to compare homogeneous samples, that is, not to collect from the literature lists of C stars identified spectroscopically of from different photometric criteria. For example, the $B_j - R$ criterion used by Totten & Irwin (1998), Whitelock, Irwin & Catchpole (1996) or Kunkel, Irwin & Demers (1997), to select C star candidates for spectroscopy, is not at all equivalent to the (CN – TiO) criterion adopted by Brewer, Richer & Crabtree (1995) and our series of investigations. This is why this paper follows strictly the photometric criteria previously used. In this way the same C star population will be revealed in a number of dwarf galaxies of different properties.

2. OBSERVATIONS AND DATA REDUCTION

2.1. The Las Campanas data

The NGC 6822 survey employs two set of observations obtained by rather different telescopes and with different procedures. The Swope telescope, on Las Campanas, was used in October 1999 to secure images of NGC 6822 in Kron-Cousins R_{KC} , CN (810 nm) and TiO (770 nm) filters. The goal of this brief survey was to identify C stars, from the color-color diagram, for follow-up spectroscopy. Thus, it was deemed unnecessary to acquire I images. A pseudo i magnitude was calculated by adding the CN and TiO magnitudes. The narrow interference filters, used here, have a FWHM of 30 nm and are the ones used in our previous surveys (Albert et al. 2000; Battinelli & Demers 2000; Demers & Battinelli 2001). The 2048×2048 SITE#1 CCD yields a field of view of $23.7' \times 23.7'$. Two slightly overlapping fields were observed for a total of five hours. Dome flats were obtained through each filters. Calibration to the standard R system was done with Landolt's (1992) equatorial standards observed during the course of the nights. This was done simply to set the magnitude zero point, not as an absolute color calibration. No calibration is done for the CN and TiO filters because we are interested only in the CN – TiO color index and their exposure times are always equal.

After the standard prereduction of trimming, bias subtraction, and sky flat-fielding, the photometric reductions were done by fitting model point-spread functions (PSFs) using DAOPHOT/ALLSTAR/ALLFRAME series of programs (Stetson 1987, 1994) in the following way: we combine, using MONTAGE2, all the images of the target irrespective of the filter to produce a deep image devoid of cosmic rays. ALLSTAR was then used on this deep image to derive a list of stellar images and produce a second image where the stars, found in the first pass, are removed. This subtracted image is also processed through ALLSTAR to find faint stars missed in the first pass. The second list of stars is

added to the first one. The final list is then used for the analysis of the individual frames using ALLFRAME. This program fits model PSFs to stellar objects in all the frames simultaneously. The journal of these observations is presented in Table 1.

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2.2. The CFHT data

NGC 6822 was also observed with the CFH12K at the beginning of one night in September 2000. The camera consists in a $12K \times 8K$ pixel mosaic covering a field of $42' \times 28'$. Each pixel corresponding to 0.206 arcsec. Images were obtained through Mould I and R filters and CN and TiO. The CFHT narrow band filters have, however, about half the bandwidth of the Las Campanas ones thus requiring relatively longer exposure times. The journal of these observations is also given in Table 1.

Preanalysis of our data was done with the FITS Larges Images Processing Software (FLIPS) package at the CFHT Headquarters. It is a program specially designed to handle mosaic data. FLIPS corrects for the bias, dark and flat, by averaging the good exposures and rejecting the overexposed and otherwise incorrect frames, for each of the 12 CCD fields of the mosaic. It also takes into account the mask of bad pixels. A nice feature of FLIPS, compared to standard pre-reduction packages, is that it normalizes the background sky values to the most sensitive CCD of the mosaic. This results in 12 fields that are comparable and on the same magnitude scale.

There were a fringe patterns in a few CCD I frames, but no correction for the fringing was done. FLIPS allows us to correct for the fringing effect but “no correction at all” was deemed the best option. Trying to correct for that cosmetic problem often increases the

noise on the frame. On a small scale, fringing was fairly constant and in the end, our analysis packages had no difficulty accounting for that anomaly.

Data reduction was done with DAOPHOT/ALLSTAR, in a way similar to the reduction of the Las Campanas data.

2.2.1. *The CFH12K calibration*

The CFHT observations were unfortunately obtained under non photometric conditions, even though the seeing was less than one arc second. We therefore had to use local stars with published magnitudes and colors to calibrate our photometry. This, however, presented a challenge because very few publications present R–I colors. We were fortunate to obtain the NGC 6822 photometry of Gallart et al. (1996) which satisfies our needs entirely.

Using 166 stars, with colors in the range $0.0 < (R - I) < 2.0$ we obtained the following transformation equations:

$$R = r + 7,643 \pm 0.022 + 0.0040 \pm 0.0196(R - I)$$

$$I = i + 7.200 \pm 0.009 + 0.0126 \pm 0.0128(R - I)$$

The r and i magnitudes are the instrumental magnitudes calibrated to Gallart et al. (1996) photometry. We thus conclude that there is no color term and that the Mould filters provide an excellent match to the Kron-Cousins magnitudes.

The non-photometric conditions obliged us to set a zero point to the CN–TiO colors, even though exposures in each filter were of the same length. We do so by following Brewer et al. (1996) and setting the mean of the $(\text{CN–TiO}) = 0.00$ for all stars with $(R-I)_o < 0.45$ since hot stars are expected to have featureless spectra in the CN or TiO regions. Brewer et al. (1996) used V–I colors, the R–I adopted here takes into account the relationship

between the two indices. Photometry of each of the twelve CCDs was thus calibrated using several hundred stars in each one. Stars in the color range $0.2 < (R - I) < 0.65$ were selected for this zero point adjustment, taking into account the $E(R-I) = 0.20$.

3. RESULTS

3.1. The color-magnitude diagram

The global color magnitude diagram, (CFH12K data) containing some 65000 stars, is shown in Figure 1. Only stars with small photometric errors are plotted here, this explains why the fainter limits abruptly appears at $I \approx 22$, *two magnitudes below the red giant tip*. We restrict our analysis to stars for which the square root of the quadratic sum of the errors on $R-I$ and $CN-TiO$ is less than 0.100. This limit is somewhat arbitrary but is justified because the inclusion of numerous fainter stars pollutes enormously the color-color diagram without increasing the number of carbon stars.

EDITOR: PLACE FIGURE 1 HERE.

The vertical ridge, at $(R - I) \approx 0.55$ is an interesting feature usually present in deep CMD fields toward low Galactic latitudes. The blue side of this ridge corresponds to the main sequence turnoff of field G dwarfs. If we adopt $(R - I)_o \approx 0.35$ for G5 dwarfs (Cox 2000), then the $E(R - I)$ toward NGC 6822 would be ≈ 0.20 , a value identical to the one proposed by Gallart et al. (1996)

We can see right away, without the analysis of the space distribution of the C stars, that NGC 6822 extends much further than its optical image makes us believe. Figure 2 displays the CMD of the periphery of our $42' \times 28'$ field. Only stars farther than $17.1'$ (~ 2.5 kpc) from the center of the field are plotted. A weak giant branch is present. The

true extent of NGC 6822 is however quite difficult to assess from its CMD because of the heavy foreground contribution by Galactic stars. As we shall see, C stars are valuable in this respect because none are in the foreground!

EDITOR: PLACE FIGURE 2 HERE.

3.2. The color-color diagram

The color-color diagram of the whole CFH12K field of NGC 6822 is presented in Figure 3. 904 stars satisfy our criteria and are called C stars. We define, for the purpose of comparison from galaxies to galaxies, C stars as stars with $(R - I)_o > 0.90$ and, in the case of narrow CN and TiO filters, stars with $(CN - TiO) > 0.30$. This $(R - I)_o$ limit corresponds to spectral type M0, according to Bessel (1991). Battinelli & Demers (2000) and Aaronson et al. (1985) showed that $(CN - TiO)$ is very little affected by reddening. This definition is obviously restrictive, one can easily see that on Fig. 3, there are bluer C stars extending to the lower left of the C star region. With the narrow CN and TiO filters used at the CFHT, it is possible to separate C stars and M stars with bluer colors than our adopted limit. This is not the case for the wider filters used in our previous studies. The C stars identified, along with their J2000.0 equatorial coordinates, magnitudes and colors, are listed in Table 2. Star c236 is the one spectroscopically confirmed by Aaronson et al. (1984).

EDITOR: PLACE FIGURE 3 HERE.

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3.3. Comparison of the Las Campanas and CFHT results

The Las Campanas photometry (LC) yielded 688 C star candidates. A coordinate match with the CFHT candidates shows that only 542 are common to both sets. A comparison of the apparent magnitude of stars common to both sets, displayed in Figure 4, shows that a substantial number of faint C stars are missing from the LC data set. The number of C star candidates, in the LC list, could have been increased by lowering the acceptance criteria based on the photometric errors. We believe, however, that the use of the combined CN and TiO magnitudes to produce a pseudo I magnitude has lowered the photometric quality of I magnitudes compared to R magnitudes of similar brightness. This approach has obviously raised the acceptable magnitude of the LC data set but it has allowed us to identify the C star population of NGC 6822 for follow-up spectroscopy more than one year before the CFHT observations confirm the existence of a huge population.

EDITOR: PLACE FIGURE 4 HERE.

About 100 stars were identified as C stars in the LC data set but were not retained in the CFHT list. A search and match in the whole CFH12K database revealed that nearly all them can be match to stars. Some of them are just a little bit too blue to be called C stars or have a (CN–TiO) index a little too small. The majority, however can match, in position, fainter stars of various colors. This suggests that the LC stars are actually blends. The pixel scale of the Swope telescope CCD is not as good as the one of the CFHT. The LC fields extend further west than the CFH12K mosaic, three possible C stars are listed in Table 3. These candidates need to be confirmed by more accurate photometry, they were located on the edge of the Swope Telescope field and their photometric errors are, in some cases, near the limit of rejection.

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4. DISCUSSION

The mean properties of the carbon star population of NGC 6822 are nearly identical to the one of IC 1613, a dwarf irregular galaxy of lower mass but with a substantial C star population. The mean magnitude and color of the 904 C stars are: $\langle I \rangle = 19.257$ and $\langle (R - I) \rangle = 1.368$, corresponding to $\langle M_I \rangle = -4.70$ and $\langle (R - I)_o \rangle = 1.17$. Albert et al. (2000) quote $\langle M_I \rangle = -4.69$ and $\langle (R - I)_o \rangle = 1.18$ for the 195 C stars in IC 1613. The abundance of IC 1613 was estimated, from the color of the tip of the giant branch, by Freedman (1988) to be $[\text{Fe}/\text{H}] = -1.3$ a value lower than the one adopted for NGC 6822. This comparison suggests that the metallicity may have little effect on the mean M_I of a C star population.

4.1. The Bolometric magnitude distribution of C stars

Costa & Frogel (1996) were able to determine the bolometric magnitude of C stars in the Large Magellanic Cloud (LMC) from their R, I photometry. Since the newly established metallicity of NGC 6822 (Venn et al. 2001) is quite close to the metallicity of the LMC, we may assume that their equation also applies to the NGC 6822 C stars. Figure 5 displays the bolometric magnitudes of C stars, listed in Table 2. as a function of their $(R - I)_o$. Our distribution, when compared to the one of Costa & Frogel (1996) for the LMC, is truncated on the blue side due to our adoption criterion. Figure 5 does show, however, that NGC 6822 does contain one C star brighter than $M_{bol} = -6.4$, the limit according to models of Boothroyd, Sackmann & Ahern (1993). That star is c043, a bright (in I) star located near the center of NGC 6822.

EDITOR: PLACE FIGURE 5 HERE.

4.2. The known S star

Aaronson et al. (1985) spectroscopically confirmed the presence of at least one S star in NGC 6822. This star is in our database but its color indices are such that our color-color diagram cannot really distinguish it from M stars. Its magnitude and colors are: $I = 18.346$; $(R-I) = 1.340$; $(CN-TiO) = 0.056$. The bolometric magnitude of the is S star, using the same relation than for C stars, is $M_{bol} = -5.90$. Brewer et al. (1996) found a single S star among their AGB stars with a surprisingly high bolometric magnitude, -6.2 . In our coordinate system, its J2000.0 coordinates are some 10 arcsec off from the ones quoted by Aaronson et al. (1985). They are: $\alpha = 19^h45^m01.3^s$, $\delta = -14^\circ49'32.1''$. There could be other S stars in NGC 6822, spectroscopy would be needed to confirm the nature of the stars lying in between the C and M region on the color-color diagram.

EDITOR: PLACE FIGURE 6 HERE.

4.3. The spatial distribution of C stars and red giant stars

We display, in Figure 6, the 904 C stars of NGC 6822 over a $42' \times 28'$ ESO Digital Sky Image centered on NGC 6822. C stars reveal that the stellar population of NGC 6822 extends over a much larger volume than its optical image would make us believe. Furthermore, C stars are not restricted to the HI disk, nicely mapped by de Blok & Walter (2000), but are found in a spheroidal halo. Radial velocities will help establishing if the C stars follow or not the HI rotation.

EDITOR: PLACE FIGURE 7 HERE.

The surface density profile of the C stars, shown in Figure 7, is well fitted by a power law with a scale length of 3.0 ± 0.1 arcmin, corresponding to 436 pc at the distance of NGC 6822. We assume circular symmetry. The exponential profile can be followed to five scale lengths. This scale length is to be compared with $112'' \pm 50''$ given by Hodge et al. (1991).

The fact that we find intermediate age stars in the outer halo of a dwarf galaxy is surprising since the halos so far known around dwarf galaxies (Lee 1993, Minniti & Zijlstra 1997, Minniti, Zijlstra, & Alonso 1999, Aparicio & Tikhonov 2000, Aparicio, Tikhonov & Karachentsev 2000) consist of ~ 10 Gyr stars. We must stress, however, that a weak intermediate age population will be missed by a CMD approach since there is no way to distinguish intermediate and old age red giants.

Since Fig. 1 shows a well defined upper giant branch, one can select a representative sample of NGC 6822 giant stars from their position on this CMD. This would represent a mixture of old and intermediate age stars. We select, from the CMD of the whole field, giant stars in a narrow parallelogram in the magnitude range $19.5 < I < 21.3$ and with the appropriate R–I intervals, slightly variable with magnitude to take into account the sloping giant branch. More than 18000 stars are in this box, including a number of foreground stars. The smoothed surface density map of the giants is presented in Figure 8. No correction for the foreground contribution has been done here. An obvious asymmetry is seen, along the E-W axis, in the inner isodensity contours. The outermost contour, corresponding to a surface density of 13.5 stars per arcmin², is roughly elliptical with an ellipticity of $e \approx 0.1$ and a position angle of $PA \approx 60^\circ$. This is quite different from the orientation of the HI disc ($PA \approx 125^\circ$) and not align with the optical bar which is, according to Hodge (1977), at $PA = 10^\circ \pm 3^\circ$. This outermost contour has a major axis of $\sim 23'$ or 3.3 kpc at the distance of NGC 6822.

EDITOR: PLACE FIGURE 8 HERE.

EDITOR: PLACE FIGURE 9 HERE.

Since it appears that the ellipticity of the halo of NGC 6822 is small in the outer part and not evident for the inner contours, we decided to neglect it and compute radial counts in circular annuli, like we did for the C stars (Fig. 7). However, for red giants, the foreground pollution is important, we estimate it from star counts in two strips on the eastern and western sides of the field. The scale length, obtained by least square fit of the middle points of Figure 9, is $3.3' \pm 0.2$ a value similar to the one obtain from C stars. We can thus conclude that the old and the intermediate age halos have the same profile.

4.4. The C/M ratio

The size of NGC 6822, relative to our mosaic is such that it is quite difficult to evaluate the foreground contribution to the M stars seen in the color-color diagram. Furthermore, the fact that NGC 6822 is at a relatively low Galactic latitude makes the problem even worst. We evaluated the foreground by counting M stars in two strips on the eastern and western side of the field. We have of course to assume that the NGC 6822 contribution is negligible in these areas. This is not strictly true since we see a few C stars up to the edge of the field. We find that the number of M stars in NGC 6822 is sensibly similar to the number of C stars, taking into account the statistical fluctuation of the foreground M star density we obtain a global $C/M = 0.92 \pm 0.10$. The M stars counted are those with spectral type M0 or later that have $(R-I)_o > 0.90$.

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Fig. 1.— Color-magnitude diagram of the whole CFH12K field, centered on NGC 6822.

Fig. 2.— Color-magnitude diagram of the periphery of the field, farther than $17.1'$ from the center of NGC 6822. We can still see a giant a weak giant branch.

Fig. 3.— Color-color diagram of the $42' \times 28'$ field, hundreds of C stars are present. Nearly 65000 stars are plotted.

Fig. 4.— I magnitude distribution of the C stars listed in Table 2. The shaded histogram corresponds to the 426 C stars common to both the Las Campanas and CFHT data. It reveals the incompleteness of the LC data at faint magnitudes.

Fig. 5.— The bolometric magnitude of C stars as a function of their intrinsic colors.

Fig. 6.— C stars are plotted over the image of NGC 6822 from the DSS. The size of the field corresponds to the CFH12K. North is on top and East is on the left. Three C stars, listed in Table 3, are just outside the western limit.

Fig. 7.— Surface density of profile of the 904 C stars.

Fig. 8.— Smoothed isodensity contours of the red giants brighter than $I = 21.3$. No correction have been done for the foreground stars. The orientation and size of the field are like the ones of Figure 6.

Fig. 9.— Surface density profile of the red giants.